Thermistors for Temperature Measurement

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Thomas E. Osterkamp

Institute of Arctic Environmental Engineering,
University of Alaska, College, Alaska B7003

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ABSTRACT

A review of thermistor characteristics and their application in the field of temperature measurement is presented. Thermistors may be used to measure temperature to an accuracy of about 0.02°C and a precision of 0.002°C under field conditions and to an accuracy of about 0.01°C under laboratory conditions; temperature differences of 0.0001°C may be detected under laboratory conditions. Thermistor stability is very good when the special handling requirements of thermistors are taken into consideration.

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THERMISTORS FOR TEMPERATURE MEASUREMENT

INTRODUCTION

In past years there has been some adverse criticism regarding the suitability of thermistors for temperature measurements. Much of this criticism stemmed from inadequate knowledge of the special handling requirements of thermistors. These requirements are presently well understood with the result that thermistors are now being widely used in the field of temperature measurement. The purpose of this paper is to examine thermistor characteristics which are related to temperature measurement and to review the use of thermistors for these measurements.

THERMISTOR CHARACTERISTICS

Resistance vs Temperature Equations

Thermistors are manufactured from semiconductor compounds and consequently their electrical conductance falls between that of good conductors (metals) and poor conductors (dielectrics or insulators). The electrical properties of thermistors may be discussed in terms of the band theory of solids.† Freidberg[1] and Boucher[2] have given comprehensive reviews on the application of the band theory of solids to the physical properties of thermistors.

The charge carriers in a thermistor material will in general be electrons and holes and, therefore, the basic equation for electrical conductivity is

$$\sigma = \frac{1}{\rho} = ne\mu_e + pe\mu_h \tag{1}$$

where ρ is the resistivity, n and p are the electron and hole densities in the conduction band, e is the electronic charge, and μ_e and μ_h are the mobilities of the electrons and holes in the conduction band. For an intrinsic semiconductor (Kittel, p. 307)

$$n = p = AT^{3/2} e^{-B/T} \tag{2}$$

where A and B are constants and T is the temperature in °K. The electron and hole mobilities usually depend on T as a power law, which leads to

$$\rho = CT^m e^{B/T} \tag{3}$$

where C and m are constants. Taking logarithms, eq. (3) becomes

$$\ln\rho = \ln C + m \ln T + \frac{B}{T} \tag{4}$$

Since the resistance is directly proportional to the resistivity, then

$$\ln R = \ln D + m \ln T + \frac{B}{T} \tag{5}$$

where D is a constant. Eq. (5) describes the R vs T characteristics of thermistors. In principle, calibration of a thermistor at three points would be sufficient to determine the constants of eq. (5) which would then be used to calculate temperatures from measurements of thermistor resistances.

†C. Kittel, "Introduction to Solid State Physics", Wiley & Sons, New York, 1968, 3rd edition, p. 299.

However, eq. (5) is transcendental in character and is not easy to work with in practice.

In certain cases, the temperature dependence of the electron and hole mobilities may be such that the constant m~O, which yields

$$1nR = 1nD + \frac{B}{T} \tag{6}$$

from eq. (5). This is the equation generally quoted by manufacturers as representing the R vs T curves for their thermistors. Eq. (6) is also very convenient to use for circuit analysis and design but it is not sufficiently accurate for very precise temperature measurements since the constants are in reality functions of temperature.

Bosson, Gutmann and Simmons[3] have proposed the empirical law

$$1nR = A + \frac{B}{T + \theta} \tag{7}$$

where A, B, θ are constants. Eq. (7) fits experimental R vs T curves for several thermistor materials better than eq. (5) or eq. (6) over a temperature range from 200-400°K.

Stanley (see Hansen[4] p. 358) has prepared a program for the Bendix G-15D computer to evaluate the constants in eq. (7) and prepare tables of R vs T at 0.1°C intervals over the temperature range from -40°C to 35°C.

Johnson[5] has attempted to fit experimental R vs T curves for thermistors with several empirical relationships. He obtained good results with

$$1nT = A + B\ 1nR + C\ (1nR)^2 \tag{8}$$

where A, B, C are constants.

Temperature Coefficient of Resistance, Dissipation Constant and Time Constant

The temperature coefficient of resistance (sensitivity) for a thermistor is defined as

$$\alpha = \frac{1}{R}\frac{dR}{dT} \tag{9}$$

where the units are $^{\circ}C^{-1}$ or %/°C. An analytical form for α can be found from eq. (6) which yields

$$\alpha = -\frac{B}{T^2} \tag{10}$$

A thermistor is subject to self-heating (Joule heating) when a current flows through it as in a measuring process. The power supplied to the thermistor is

$$P = IV \tag{11}$$

where I is the current and V is the voltage drop across the thermistor. The power dissipated is

$$H = \delta(T - T_o) \tag{12}$$

where δ is the dissipation constant, T is the temperature of the thermistor and T_o is the ambient temperature. The dissipation constant is the power in mw which will raise the thermistor 1°C above its ambient temperature.

The rate of change of heat in the system is

$$\frac{dQ}{dt} = IV - \delta(T - T_o) \tag{13}$$

so that for steady state conditions

$$IV = \delta(T - T_o) \tag{14}$$

Eq. (14) can be used to calculate the allowable power input to a thermistor for a specified difference $T - T_o$.

The time constant of a thermistor is the time required for the thermistor temperature to change 63% of the difference between its initial temperature and a temperature impressed upon it in a step change.

APPLICATIONS

Thermometry

Thermistors used for temperature measurement are usually calibrated according to standard methods. In general, the calibration procedure will involve a comparison to a standardized thermometer or measurement of the temperatures of the fixed points on the International Practical Temperature Scale (IPTS). Extremely accurate temperature measurement also requires that differences between temperatures measured on the IPTS and on the Thermodynamic Temperature Scale be taken into consideration. This point is discussed by Beattie[6], Brickwedde[7], van Dijk[8] and Benedict[9]. The difference between the two temperature scales over the temperature range encountered in field work is probably less than 0.01°C.

Benedict[9] has recently reviewed the principles of thermometry; a short summary will be given here. The primary fixed points of the IPTS which are of interest for field work are:

—Boiling point of oxygen (equilibrium temperature between liquid oxygen and its vapor) ..... -182.970°C
—Triple point of water (equilibrium temperature between ice, liquid water and water vapor) ..... 0.0100°C
—Boiling point of water (equilibrium temperature between liquid water and its vapor) ..... 100.000°C

The triple point of water is a fundamental fixed point common to both the IPTS and the Thermodynamic Temperature Scale. In addition, secondary reference points have been established and some of these, selected from Stimson[10], are:

—Temperature of equilibrium between solid carbon dioxide and its vapor ..... -78.5°C
—Temperature of equilibrium between solid mercury and liquid mercury ..... -38.87°C
—Temperature of equilibrium between ice and air-saturated water (ice point) ..... 0.000°C

—Temperature of the triple point of phenoxybenzene (diphenyl-ether) .....26.88°C
—Temperature of transition of sodium sulphate decahydrate .....32.38°C

Experimental methods for achieving the fixed points on the IPTS and the accuracies to which these may be determined are discussed by Stimson[11]. Between the fixed points on the IPTS temperature is defined by a standard interpolation instrument (platinum resistance thermometer) used with interpolation equations. The National Bureau of Standards (NBS) maintains standard platinum resistance thermometers. NBS also calibrates other thermometers by comparison to the standard platinum resistance thermometers. These calibrated thermometers are then said to be traceable to NBS standards and are in turn used to calibrate other thermometers in laboratories throughout the country.

Calibration Methods

It is convenient to discuss calibration methods for thermistors according to the accuracy required for the temperature measurements. The R vs T charts and graphs supplied by thermistor manufacturers are usually sufficient to determine temperatures to an accuracy on the order of 1°C. However, it would be well to obtain a check on these charts by measuring the temperature of one fixed point in the temperature range where the thermistor is to be used. The ice point would suffice for most field applications of thermistors and it is especially convenient to use.

Thermistors may be calibrated by comparison to standard thermocouples or standard liquid-in-glass thermometers (traceable to NBS standards) when the required accuracy of the temperature measurement is in the range from 0.1°C to 1.0°C. Again, an ice bath may be used to obtain a check on the calibration accuracy.

When the required accuracy is in the range from 0.01°C to 0.1°C, thermistors may be calibrated by comparison to a standard platinum resistance thermometer (traceable to NBS standards) and by measuring the temperature of a carefully prepared ice bath. Swindells[12] (p. 342) has described the preparation of an ice bath which realizes the ice point to an accuracy better than 0.01°C.

Thermistor calibration to an accuracy better than 0.01°C can be made by comparison to a standard platinum resistance thermometer (traceable to NBS standards) and by measuring the triple point of water using a triple point cell. However, the problem of thermistor stability would make the value of such an accurate calibration somewhat dubious over long time periods.

The purpose of thermistor calibration is to secure a graph or table of R vs T values. Obviously, it would be impractical to obtain R vs T values for all possible temperatures to be measured by a thermistor. A practical method of thermistor calibration is to select one of eqs. (5)-(8) as an interpolation formula. Subsequent calibration at two or three temperatures is sufficient to determine the constants in the equation which can then be used to prepare a graph or table of R vs T values. Unfortunately, the constants of eqs. (5)-(8) have a small temperature dependence. This restricts the temperature range for which the constants are valid and in general the more stringent the accuracy requirements the greater the restriction.

Accuracy and Precision

The accuracy of thermistor temperature measurements is determined by the temperature range, thermistor stability and the accuracy of the instrument used to measure the thermistor resistance.

Beck[13] has found that, for eq. (6), the range over which one pair of constants can be used to give temperatures to an accuracy of 0.01°C varies from 6-12°C. Lachenbruch et al.[14] used eq. (7) as an interpolation formula for thermistors used in measurement of permafrost temperatures. These authors calibrated thermistors at 15° intervals from -30°C to +30°C by comparison to a standard platinum resistance thermometer and measurement of the ice point. They found that temperature measurements could be made to an accuracy of ±0.02°C in the field and ±0.01°C in the laboratory and that temperature differences could be measured by the same thermistor with an accuracy of ±0.01°C in the field and ±0.001°C or less in the laboratory. Ross (Hansen[4], p. 357) found that the deviation of computed values of temperature using eq. (7) from the observed temperatures does not exceed 0.025°C over the range from -40°C to 35°C and that the deviation could be reduced to less than 0.01°C by calibrating at 15°C intervals over the desired range.

Hansen[4] considers the precision (reproducibility) of thermistor temperature measurements in permafrost to be about 0.002°C. Baker, Ryder and Baker[15] state that sporadic resistance fluctuations limit possible precision to about ±0.002°C for thermistor temperature measurements.

Thermistors have been used to measure temperature differences on the order of 0.0001°C by Müller and Stolten[16] and Vanderborgh and Spall[17].

Stability

Thermistor stability is determined to a large extent by the treatment accorded thermistors before and during temperature measurements. Some factors which may have an adverse effect on thermistor stability are:

—Use of thermistors over a large temperature range.
—Mechanical and thermal shock.
—Exceeding the specified maximum power rating.
—Failure to pre-age thermistors.
—Interruption of the current to the thermistor between measurements.
—Measurement of temperatures outside the specified temperature range.

Stability tests on thermistors by Droms[18] indicate that thermistor beads sealed in glass probes are the most stable type. These units were exposed to a temperature of 100°C for long periods of time and their calibration change at the ice point was less than 0.03°C. Similar units exposed to 200°C temperatures for the same length of time changed calibration at the ice point by an order of magnitude more than those maintained at 100°C.

Lachenbruch et al.[14] found that for temperature data taken with thermistors in permafrost below 300 feet the standard error from a straight line diminished from 0.05°C to 0.02°C over an eight-year period, which indicates a high degree of stability. Thermistors used by Müller and Stolten[16] over a 2°C range in the vicinity of 25°C remained stable to better than 0.0001°C for periods up to 30 minutes and were stable to 0.02°C for a period of six months (see Beck[13], p. 16). Beck[13] found that under field conditions over a temperature range of 10°C relative temperatures may be relied upon to an accuracy of 0.02°C for at least 17 months. He also found that cycling a thermistor to a temperature 10°C higher than the temperature at which it was used previously (thermal shock) resulted in a subsequent error in temperature measurement of about 2°C.

Both Boucher[2] and Beck[13] have commented on the important of protecting thermistors from mechanical shock. The present author has also experienced thermistor deterioration due to mechanical shock.

Boucher[2] recommends aging thermistors by passing current through them for several hundred hours at the maximum temperature at which they will be used. Hansen[4] recommends an alternate procedure which consists of cycling the thermistors between the boiling point of water and the sublimation temperature of carbon dioxide. The thermistors are used to measure the triple point of water after each period at the boiling point and those thermistors which remain stable to within 0.002°C at the triple point are calibrated.

Müller and Stolten[16] found that thermistor stability was improved by keeping a small voltage across the thermistor at all times—even when it was not in use. Jordan[19] also recommends passing a small current (100-1,000 μa) through the thermistor at all times to improve its stability.

Practical Aspects

Thermistors are generally available for temperature measurements from -60°C to 300°C. These thermistors may be obtained with time constants ranging from about 0.1 sec to more than 100 sec. The dissipation constants commonly range from 0.01 mw/°C to more than 100 mw/°C.

Detailed calibration techniques and the problem of self-heating are discussed by Jones[20]. The maximum permissible current for a given self-heating rise in thermistor temperature is given as

$$I_m = \left[\frac{\delta T_s}{R}\right]^{1/2} \tag{15}$$

where T_s is the permissible self-heating rise in thermistor temperature. Eq. (15) can be derived directly from eq. (14). If the upper limit to permissible self-heating is set at one-half the temperature accuracy required, then

$$T_s = 1/2\ (\%\ \text{Resistance accuracy desired})/100\alpha \tag{16}$$

As an example, suppose it is desired to measure temperature to an accuracy of 0.10°C using a thermistor with a dissipation constant of 0.7 mw/°C and a resistance of 10,000 ohms at the temperature to be measured. Then the permissible self-heating should be held to one-half the desired accuracy or 0.05°C. The maximum permissible current in the thermistor is

$$I_m = \left[\frac{0.7 \times 0.05\ \text{mw}}{10{,}000\ \text{ohms}}\right]^{1/2} \tag{17}$$

or

$$I_m \sim 59\mu\text{a} \tag{18}$$

If a bridge is used to measure the thermistor resistance, then the voltage across the thermistor should be 0.59 v or less in this example.

Usually it is not necessary to compensate for lead resistance when making temperature measurements with thermistors. However, it will be necessary to do so when the leads are very long and high accuracy is required for the measurements.

Interchangeability of thermistors is poor when high accuracy is required. This necessitates individual calibration of thermistors for accurate temperature measurements. However, Schiff[21] has described interchangeable thermistors which follow the same R vs T curve to an accuracy of 0.1°C.

Thermistor lifetime appears to depend on the severity of the operating conditions. In general, those factors which affect the stability of thermistors also tend to shorten their usable lifetime.

Thermistors are sensitive to both light (radiation) and pressure although there does not appear to be much data available in the literature. Baker, Ryder and Baker[15] state that pressure variations do not exceed 0.001°C/atm.

REMARKS

It appears that thermistors may be used to measure temperatures to an accuracy of about 0.02°C and a precision of 0.002°C under field conditions and to an accuracy of about 0.01°C under laboratory conditions. Temperature differences of about 0.0001°C may be detected under laboratory conditions. Thermistor stability is very good when the special handling requirements of thermistors are taken into consideration. These requirements are not so restrictive that they detract from the general usefulness of thermistors for temperature measurements.

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REFERENCES

[1]S. A. Freidberg, in "Temperature, Its Measurement and Control in Science and Industry", Reinhold Publishing Corporation, New York, 1955, Vol. 2, p. 359.

[2]E. A. Boucher, J. Chem. Ed. 44(11), A935, (1967).

[3]G. Bosson, F. Gutmann and L. M. Simmons, J. Appl. Phys. 21, 1267 (1950).

[4]B. L. Hansen, National Academy of Science, National Research Council Publication No. 1287, Washington, D. C., p. 356.

[5]P. R. Johnson, Institute of Arctic Environmental Engineering, University of Alaska, College, Alaska, private communication.

[6]J. A. Beattie, in "Temperature, Its Measurement and Control in Science and Industry", Reinhold Publishing Corporation, New York, 1955, Vol. 2, p. 91.

[7]F. G. Brickwedde, in "Temperature, Its Measurement and Control in Science and Industry", Reinhold Publishing Corporation, New York, 1962, Vol. 3, Part I, p. IX.

[8]H. van Dijk, in "Temperature, Its Measurement and Control in Science and Industry," Reinhold Publishing Corporation, New York, 1962, Vol. 3, Part I, p. 177.

[9]R. P. Benedict, "Fundamentals of Temperature, Pressure and Flow Measurements", Wiley & Sons, Inc., New York, 1969, p. 29.

[10]H. F. Stimson, in "Precision Measurement and Calibration, Temperature", NBS Special Publication 300, 1968, p. 19-1.

[11]H. F. Stimson, in Precision Measurement and Calibration, Temperature", NBS Special Publication 300, 1968, p. 121-141.

[12]J. F. Swindells, in "Precision Measurement and Calibration, Temperature", NBS Special Publication 300, 1968, p. 336-1.

[13]A. Beck, J. Sci. Instr. 33, 16 (1956).

[14]A. H. Lachenbruch, M. C. Brewer, G. W. Greene and B. V. Marshall, in "Temperature, Its Measurement and Control in Science and Industry", Reinhold Publishing Corporation, New York, 1962, Vol. 2, Part I, p. 791.

[15]H. D. Baker, E. A. Ryder and N. H. Baker, "Temperature Measurement in Engineering", Wiley & Sons, Inc., New York, 1961, Vol. 2, p. 5.

[16]R. H. Müller and H. J. Stolten, Anal. Chem. 25 (7), 1103 (1953).

[17]N. E. Vanderborgh and W. D. Spall, Anal. Chem. 40(1), 256 (1968).

[18]C. R. Droms, in "Temperature, Its Measurement and Control in Science and Industry", Reinhold Publishing Corporation, New York, 1962, Vol. 3, Part II, p. 339.

[19]J. Jordan, in "Treatise on Analytical Chemistry", Interscience Publishers, New York, 1968, Vol. 8, p. 5207.

[20]E. W. Jones, Instr. Control Systems, 38, 123 (1965).

[21]R. I. Schiff, "Temperature Measurement and Control Handbook", Instr. Control Systems, Pittsburgh, Pa., 1966, p. 17.

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